N74-10294

Paper No. 74

HEAT TRANSFER AT SUBATMOSPHERIC PRESSURES I.

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ABSTRACT

A study was performed to measure heat transfer rates between surfaces at conditions experienced in space environment simulation chambers. Many of these conditions are also similar to those experienced in general cryogenic systems.

This study was performed to obtain data more directly applicable to space environment and cryogenic applications, using large temperature differentials and distances between surfaces of up to 40 cm. Previous investigations have been directed at determining the properties of the gases studied, mainly thermal conductivity. In those prior studies, hot wires in tubes and precision parallel plate and concentric cylinder devices were used. The data of this investigation was taken in a 1 meter diameter space environment simulation chamber examining heat transfer between 3.8 cm and also 10 cm diameter Boelter-Schmidt type heat flux meters at ambient temperature and a one meter by one meter square liquid nitrogen-cooled flat panel. The pressure range investigated was from 10^{-5} torr to one atmosphere. Two surfaces were investigated, matte black velvet and aluminized Kapton, to provide extreme cases. The distances between surfaces varied from 0.05 to 40 cm. The gas evaluated in this study was nitrogen.

INTRODUCTION

Investigations and studies have been made on thermal conductivity and heat transfer rates in rarified gases. In these investigations the mechanisms of heat (energy) transfer were studied and properties of the gases determined. These studies were necessarily conducted at precisely controlled conditions selected to give data that required minimal mathematical complexity in interpreting. For example, three basic geometries were studied: parallel semi-infinite planes, concentric cyclinders, and concentric spheres. Further, temperature differentials were kept minimal so error in assigning a mean temperature of the gas between the two heat transfer surfaces would be minimized. However, in space environment simulation and general cryogenic applications, heat transfer problems involving rarified gases (pressures one atmosphere or less) usually involve large temperature differentials, large distances and a variety of geometries. It is the purpose of this investigation to determine heat transfer rates for conditions encountered in the practice of space environment simulation testing and cryogenic systems. Included in the investigation are the large temperature differentials and nonideal geometries. It is hoped that useful and practical data are presented in this paper for ready use by those confronted with such problems.

THEORY

An introduction to gaseous heat transfer is given by Kennard (1). A survey and digest of heat transfer investigations is offered by Springer (2). A very thorough description of thermal conductivity measurements in gases is presented by Tsederberg (3) except for the technique used in this investigation.

Depending upon the pressure of the gas and the distance between heat transfer surfaces, heat transfer in static gases can be considered to have four different modes. The condition of pressure and intersurface distance is described by the Knudsen number, λ/D, where λ is the mean free path of molecules of the gas colliding with one another and is a function of gas pressure, temperature, and molecular diameter, and D is the "characteristic dimension" of the heat transfer system closely describing the mean heat transfer path. The condition where the Knudsen number is greater than 10 is considered as the molecular heat transfer regime, where heat is transferred by single molecules colliding only (or in a great majority) with the walls. The Knudsen number range 10 to 0.01 is known as the "transition" range, wherein the mechanism is ill defined, being a combination of single molecular transfer between surfaces and a small number of intermolecular collisions before striking the second surface. When the Knudsen number is less than 0.01, heat conduction is said to take place by the laminar, viscous, or continuum regime. Heat is conveyed from a surface to a layer of gas adjacent to it, and from that layer to the next, et cetera. An important characteristic to all modes of heat transfer, expecially molecular, is the ability of a molecule of a gas to adjust its temperature toward that of the wall when it collides with the wall. This property, dependent upon the gas, gas temperature and the wall, is known as the accomodation coefficient (α). The accommodation coefficient is zero if the temperature of a gas molecule is unchanged by colliding with a surface of different temperature, and unity if the molecule achieves the temperature of the wall with one collision.

Molecular regime heat conduction increases linearly with density. A gas offers more carriers per unit area with increased density and also linearly with velocity, which is the rate of traverse of a single molecule from one surface to the other. Since density is proportional to the ratio of pressure over temperature, and velocity is proportional to the square root of kinetic energy, which, in turn, is proportional to temperature, heat conduction in the molecular regime is directly proporational to pressure and inversely proportional to the square root of the velocity. From a kinetic standpoint, the rate is inversely proportional to the square root of molecular weight of the gas and thermodynamically the heat transfer rate is directly proportional to the heat capacity of the gas. Free molecular conduction is proportional to the accommodation coefficient, but not as simply as might be suspected. A composite accommodation coefficient must be used if two different surfaces are involved:

$$\alpha = \frac{\alpha_1 \times \alpha_2}{\alpha_1 + \alpha_2 - \alpha_1 \alpha_2}$$

which reduces to $\alpha = \frac{\alpha_1}{2-\alpha_1}$ when both surfaces are identical. A unique and important feature of molecular conduction is that it is independent of path length, providing that the mean free path exceeds ten times that path. This is evident when it is considered that molecular heat transfer is the product of number of molecules per unit area, velocity of the molecules, heat capacity of the molecule, and efficiency of the molecules to transfer heat with the surfaces.

Laminar or continuum heat conduction is dependent upon path length and independent of pressure. The dependency upon path length arises from the increased number of lamina which transfer heat from one to another as the path increases. The independence of pressue exists because, although the number of molecular carriers per unit area increases with density, the number of lamina per unit length also increases and causes the effects to cancel each other. Due to the effect of velocity on the rate of energy transfer the heat transfer coefficient (thermal conductivity) of the gas in the continuum regime should be proportional to the square root of the gas temperature.

The fourth mode of heat transfer in a static gas is natural convection. This appears when the gas becomes dense enough that gases at higher temperature will decrease in density and tend to rise and those colder tend to fall. This phenomenon would not be expected in the absence of a gravity field. Because of gravity dependence we should expect natural convection to be highest for a warm horizontal surface facing up, lowest for a warm horizontal surface facing down (the surface hindering upflow of the gases it has heated), the opposite situation for a cold surface, and in the case of warm or cold surface, natural convection at a vertical surface would be in between those rates for upward and downward facing horizontal surfaces. A "warm" surface is a surface warmer than the gas, and a "cold" is a surface cooler than the gas.

All forms of heat conduction in static gases are also geometry dependent. For the continuum regime, the geometric problem is treated as is the Fourier relationship for isotropic solids. The effect of geometry is somewhat more subtle for molecular flow (ref. 1 and 2), and very complex for natural convection. For example, in convective transfer between a large and a small surface, the transfer rate would be determined mainly by the orientation of the small surface since the bulk of the gas may be considered as conditioned to the temperature of the large surface. This effect becomes ambiguous as the sizes of the two surfaces approach one another. Further, natural convection is dependent upon the distance between two surfaces. If the distance is small enough continuum conduction will dominate the heat transfer (since it is inversely proportional to path length), and as the distance increases natural convection will interfere and eventually dominate the heat transfer.

The investigation undertaken measured the actual heat transfer rates for simple geometries (two parallel vertical surfaces, the cold surface large and the warm surface small) in a common rarified gas (nitrogen). Due to the lack of ideal conditions, such as small temperature differentials and semi-infinite planes, the data obtained is difficult to relate to theory. On the other hand, the data is very practical since the conditions studied are similar to those encountered in cryogenic and space environment simulation practices.

INVESTIGATION

A unique calorimetric technique was used to obtain the heat transfer data. A windowless Hy-Cal P8400 radiometer was used as the heat transfer sensor. The radiometer diameter is 1.5-inch and has an aluminum body through which water flowed at a rate of 0.3 gallons per minute. The sensitivity of the radiometer was approximately 42 BTU/ft hr/millivolt. A copper-constantan thermocouple was mounted on the copper tubing water line within 1/2-inch of the radiometer. The water line was bent in a loop to permit translation of the radiometer without kinking the copper tubing. The water line was wrapped with aluminized Kapton film to isolate the water from the environment. The study was performed in a cylindrical vacuum chamber (Chamber N of the Space Environment Effects Laboratory, Johnson Space Center - see fig. 1) which contained a concentric cryogenically cooled shroud 36-inches in diameter and 36-inches long. The axis of the chamber is horizontal. A 36-inch square aluminum plate with an 8inch diameter liquid nitrogen-cooled "wart" in its center was placed vertically in the chamber. The plate and the cryogenic walls were instrumented with thermocouples. The radiometer was mounted on a 0.5-inch diameter stainless steel rod that was supported by a "push-pull" feed-through. This penetration was located midway along the chamber horizontal (cylindrical) axis and along a horizontal radial line intercepting the center of the cylindrical cross section. The radiometer could be moved along a normal line through the vertical plate's center. The liquid nitrogen-cooled "wart" was on the side of the plate opposite the side facing the radiometer. The shroud was cooled with liquid nitrogen and all experiments were conducted with all plate and shroud temperatures of -280^{o} F to -315^{o} F. The radiometer water temperature was controlled by a cooling/heating servo-regulated circulating system of water-glycol.

Chamber pressures were measured by a Varian millitorr gage in the range of 10^{-6} to 10^{-2} torr, an alphatron gage in the range of 10^{-4} to 100 torr, and a Wallace and Tiernan Bourdon-type gage in the range of 0.3 to 760 torr. The distance between the radiometer face and the vertical plate was measured in the range of 0.05 to 2 cm with a cathetometer located at the front of the chamber, sighting through a glass viewport. Distances in the range 2 to 39 cm were measured

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by a marker placed on the traversing rod which pointed to a fixed meter scale.

The gas selected was nitrogen because it is commonly used in space environment simulation and is the most common gas used in cryogenic engineering. Thermally, nitrogen is almost identical to air, except that problems involving partial condensation of oxygen at high pressures and liquid nitrogen temperatures can be avoided by using pure nitrogen. The nitrogen used for this investigation was water pumped and oil free.

Two radiometer surfaces were employed, first 3M Nextel 410C flat black and for a second study the radiometer surface was covered with aluminized Kapton film (aluminized side out) which was applied using 3M No. 467 tape adhesive. These coatings were selected to provide extremes in accommodation coefficients. The spongy black surface was expected to have a higher heat transfer rate than the specular aluminized surface

To isolate radiative transfer from conductive and convective, a series of data were taken at ultimate vacuum (less than 10^{-6} torr). The radiometer signal for various gas pressures was corrected by subtracting the radiometer output measured at high vacuum at the corresponding distances. The radiometer output stability was approximately 5 microvolts, corresponding to approximately 0.2 BTU/ft^2-hr. Radiometer temperature was recorded for each reading.

The radiometer was calibrated when the high vacuum readings were taken for the flat black case. The technique of data interpretation is described in reference (4), and simply involves measuring radiometer output at a known temperature in a cryogenic environment of known temperature. The radiometer signal is proportional to the heat exchanged.

$$S = \frac{\epsilon\sigma[T_r^4 - T_W^4]}{mv}$$

where mv = radiometer millivolt output @ 1×10^{-5}torr or less

S = radiometer sensitivity

ϵ = emittance of 3M Nextel flat black paint = 0.89

σ = Stefan-Boltzmann constant, 0.173×10^{-8} btu/ft^2-hr °R^4

T_r = radiometer temperature °R

T_W = wall temperature °R

The calibration data was selected from the 20 cm distance readings to avoid effects of re-reflection of infrared radiation of close surfaces. Re-reflected radiation complicates the determination of heat exchange. This calibration is valid when the radiometer has the aluminized film applied to it because it pertains only to the heat passed through the sensing slab which is underneath the film of paint.

For all measurements, the following heat transfer paths were investigated: 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, and 39.0 cm. For the 3M black painted surface, sensor temperature was 90° F and pressure range studied was 10^{-4} to 3 torr. For the aluminized Kapton case, the pressure range was 10^{-4} to 10 torr for a 90° F sensor and 10^{-4} torr to 760 torr for a 30° F sensor.

RESULTS

The results of this study are tabulated in Tables I, II, and III and are depicted graphically in Figures 2, 3, and 4: The molecular regime, transition regime, and laminar or continuum regime boundaries are also illustrated in the figures, as defined according to the Knudsen number.

DISCUSSION

All three cases studies (3M black at 90° F, aluminized Kapton at 90°F, and aluminized Kapton at 30°F) appeared to demonstrate the same general behavior as a function of pressure and transfer path length. The heat transfer for the 30° F aluminized surface was disproportionately lower than that for the same surface at 90° F. The heat transfer for the aluminized surface at 90° F was higher than that of the 3M black surface at the same temperature but within the same order of magnitude. This result is unexpected, since it was assumed that a specular aluminized surface would have a low accommodation coefficient and a rough, spongy surface as 3M black would be much higher. Thus the heat transfer for the black surface should have been much greater than for the aluminized surface.

The results do demonstrate "textbook" style that the heat transfer is independent of distance in the molecular regime and is independent of pressure in the continuum regime. Figure 5 is a plot of heat transfer versus distance in the continuum regime at fixed pressures and demonstrates that in this regime heat transfer is inversely proportional to the path and independent of pressure, providing the convective contribution is negligible. The convection causes the anomalies in the region of high pressure and large path length.

The very interesting case of natural convection is evidenced in figure 4. It is first evident at large distances, where conduction is subdued by the greater path, but as pressure increases, the convection increases so as to become evident even at 0.5 cm distance at 100 torr pressure. It is also evident from figure 4 that the actual amount of convective transfer is independent of the path and increases linearly with pressure. If the heat transfer curve for the 10 cm case in figure 4 is extrapolated horizontally from the incipience of the continuum to 760 torr and the difference between this pure conductive transfer and total transfer be attributed to natural convection, the natural convective heat transfer as a function of pressure would be the values presented in figure 6.

In figure 6, the values of heat transfer at distances of 5, 10, and 20 cm were averaged for each pressure, and 30 BTU/ft^2 hr was subtracted from the average for each pressure. The quantity 30 BTU/ft^2 hr is the value of conductive heat transfer just after which convective heat transfer becomes apparent (fig. 4). The lengths 5, 10, and 20 cm were selected because the convective component of transfer was apparent at pressures down to 10^{-1} torr, giving seven data points for interpretation. The graph of figure 6 indicates that convective heat transfer Q_v is a function of pressure P according to the relationship $Q_v = aP^b$, where a and b are constants, and figure 4 indicates that Q_v is independent of length. A least squares solution for the constants from the seven data points is a = 8.04 and b = 0.5669, or $Q_v = 8.04\ P^{0.5669}$, when Q_v is in BTU/ft^2 hr and P is in torr. The standard deviation of the data points from the values determined by the equation is 13.2 percent, which is ordinarily a poor fit, but considering we are quantitatively handling convection, this is quite good.

It should be pointed out again that this data is for specific geometries; a small warm surface and a very large cold surface, and some caution must be taken when applying this data to other conditions. The appearance of the data indicates, however, that in going from a parallel semi-infinite plane condition (0.05 to 0.5 cm) to a remote point source condition (10 to 39 cm) the heat transfer follows in parallel patterns. This indicates that the error may not be too great in applying this data to a wide variety of conditions. The convective data, though, is strictly for the vertical warm surface case, and will certainly be different for horizontal surfaces, depending on their viewing up or down and being hot or cold.

Accommodation coefficients were calculated from the data, and showed for 3M velvet to be 0.35 and for the aluminized specualr surface to be 0.374 and 0.408. The former value was calculated from the 90° F data and the latter value from the 30° F data. The values for the specular surface are larger than expected. No explanation is offered. The accommodation coefficient for the spongy, matte 3M black surface is lower than an expected value of near unity, but when adsorption and even entrainment of nitrogen molecules in the microscopically irregular surface is considered, low accommodation coefficient may be explained. In the case of adsorption or entrainment, the molecules are temporarily arrested at the painted surface, slowing their effective net heat transfer velocity, that velocity being the distance traversed divided by the sum of the time to traverse it at the mean velocity and the time the molecule is delayed at the surface.

Some useful heat transfer values were obtained for static nitrogen gas in the range 10^{-3} to 760 torr at path lengths ranging from 0.05 to 20 centimeters. The data demonstrated behavior agreed with theory concerning heat transfer in the molecular and continum regimes. Exact calculations for comparison were not possible due to the uncertainty of mean gas temperature because temperature differentials were very large. Convective heat transfer for a vertical smooth surface in a nitrogen atmosphere was empirically correlated to pressure at a given large temperature differential, and was shown to be independent of path length.

CONCLUDING COMMENTS

It is evident from the limited number of cases studied and from the large number of important cases encountered that more data are necessary. Other gases should be investigated, including helium, argon and methane. Studies should be performed for temperatures ranging from -200° F to $+250^{\circ}$ F. Further, data should also be obtained for a surface facing up and a surface facing down. Structural metal surfaces should be studied, such as aluminum, stainless steel, and copper.

ACKNOWLEDGEMENTS

The authors are grateful to the Space Environment Test Division of the Lyndon B. Johnson Space Center for providing the facilities and permission to conduct this investigation. Mr. R. L. Anderson of the SETD Operations Engineering Section is acknowledged for suggesting this type of study. The authors are very grateful to the engineers and technicians of the Space Environment Effects Laboratory of Northrop Services, Inc., Houston, Texas who assisted in the test setup and taking of the measurements and, in particular, we wish to thank Mr. Gerry Udvardy of Northrop for his efforts.

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TABLE I.- COMBINED CONDUCTIVE-CONVECTIVE HEAT FLUX IN BTU/FT HR FOR VERTICAL SPECULAR ALUMINIZED SURFACE AT 30 °F, -300 °F ENVIRONMENT, NITROGEN GAS

d-DISTANCE IN cm \ PRESSURE IN TORR	1.5×10^{-3}	5×10^{-3}	1.5×10^{-2}	6.2×10^{-2}	3.6×10^{-1}	1.0	3.0	10.0	30.0	100.0	300.0	500.0	760.0
0.05	13.7	50.7	146	399	-	-	-	-	-	-	-	-	
0.1	14.1	54.5	134.	332	486	533	553	549	553	553	551	556	562
0.2	13.7	51.4	117.	249	323.	360.	360.	366.	370.	370.	389.	377.	394.
0.5	13.3	40.7	86.	145.	170.	177.	180.	181.	182.	203.	248.	270.	324
1.0	12.6	35.0	67.	84.	102	105.	105.	107.	117.	156.	236.	294.	364
2.0	11.8	29.0	49.	57.	61.	61.	62.	69.	87.	151.	222.	279.	367
5.0	9.9	21.7	35.	37.	36.	43.	53.	61.	84.	141.	221.	278.	328
10.0	8.7	17.9	27.4	30.	28.	61.	63.	86.	102.	146.	212.	248.	301
20.0	7.2	14.1	22.	23.	24.	41.	59.	63.	81.	127.	198.	236.	308
39.0	6.8	14.1	21.7	19.	-	-	-	-	-	-	-	-	-

TABLE II.- COMBINED CONDUCTIVE-CONVECTIVE HEAT FLUX IN BTU/FT HR FOR VERTICAL MATTE BLACK SURFACE AT 90 °F, -300 °F ENVIRONMENT, NITROGEN GAS

d-DISTANCE IN cm \ PRESSURE IN TORR	5×10^{-4}	1.5×10^{-3}	5.3×10^{-3}	1.2×10^{-2}	4.2×10^{-2}	1.1×10^{-1}	3.2×10^{-1}	9.4×10^{-1}	3.0
0.05	7.1	12.7	48.	121.	384.	581.	881.	1164.	1633.
0.1	5.4	12.6	47.	108.	323.	461.	583.	840.	926.
0.2	7.9	14.7	46.	100.	249.	346.	466.	474.	473.
0.5	5.1	13.	40.	77.	158.	203.	217.	225.	237.
1.0	4.3	11.9	33.	56.	91.	103.	109.	112.	109.
2.0	3.9	11.1	28.	44.	62.	67.	71.	71.	71.
5.0	2.9	8.6	21.	31.	39.	41.	41.	43.	51.
10.0	2.6	7.8	18.	24.	30.	29.	30.	40.	51.
20.0	.9	7.1	15.	20.	23.	22.	27.	40.	54.
39.0	.1	6.3	14.	20.	22.	22.	27.	39.	52.

TABLE III.- COMBINED CONDUCTIVE-CONVECTIVE HEAT TRANSFER IN BTU/FT HR FOR VERTICAL SPECULAR ALUMINIZED SURFACE AT 90 °F, -300 °F ENVIRONMENT, NITROGEN GAS

PRESSURE IN TORR / d- DISTANCE IN cm	1.5×10^{-5}	4.7×10^{-4}	1.5×10^{-3}	5×10^{-3}	1.5×10^{-2}	5×10^{-2}	2.1×10^{-1}	4×10^{-1}	1.0	3.0	10.0		
0.05	1.9	4.9	15.2	51.1	180.6	493.3	1254	1540	1711	2290	2314		
0.1	1.5	4.6	14.5	50.4	161.3	407.2	919	1030	1177	1242	1234		
0.2	1.9	4.9	14.5	48.1	139.4	301.6	535	608	548	652	644		
0.5	1.9	4.9	14.1	41.9	102.4	172.5	236	248.3	277.7	263	251.6		
1.0	1.9	4.2	12.2	33.9	71.4	110.5	129	126.8	128.2	132.2	139.5		
2.0	1.5	4.2	11.4	29.0	54.1	71.7	76.2	77.4	76.6	79.7	91.9		
5.0	1.5	3.8	10.3	22.5	37.8	46.1	44.2	45.0	46.1	57.6	66.0		
10.0	1.1	3.8	9.51	18.7	28.9	33.9	32.7	33.9	38.5	58.4	68.9		
20.0	1.5	3.8	8.4	16.0	22.9	23.2	26.3	30.9	39.6	61.4	75.8		
39.0	1.5	3.4	5.0	15.6	22.1	22.4	27.1	31.6	39.5	59.1	77.0		
[a]0.1	1.9	4.9	14.4	49.6	161.3	410.	935	1082	1169	1363	1524		

[a] REPEAT TEST

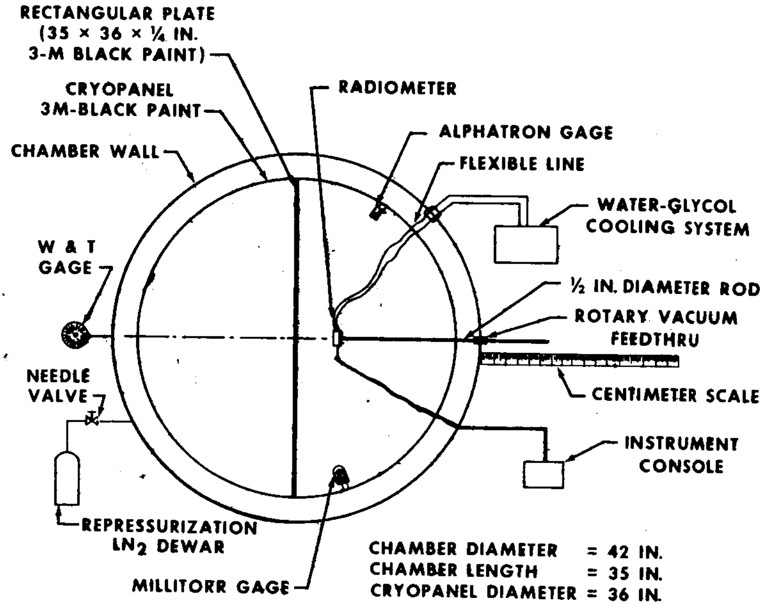

Figure 1.- Experimental configuration.

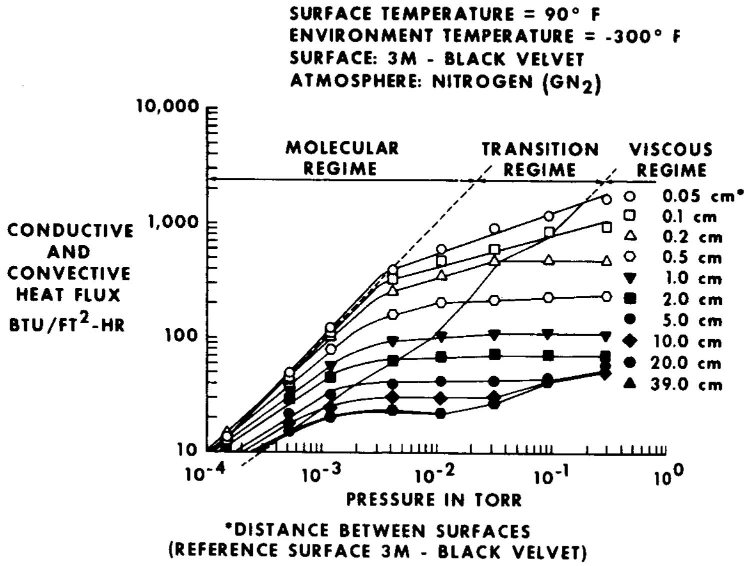

Figure 2

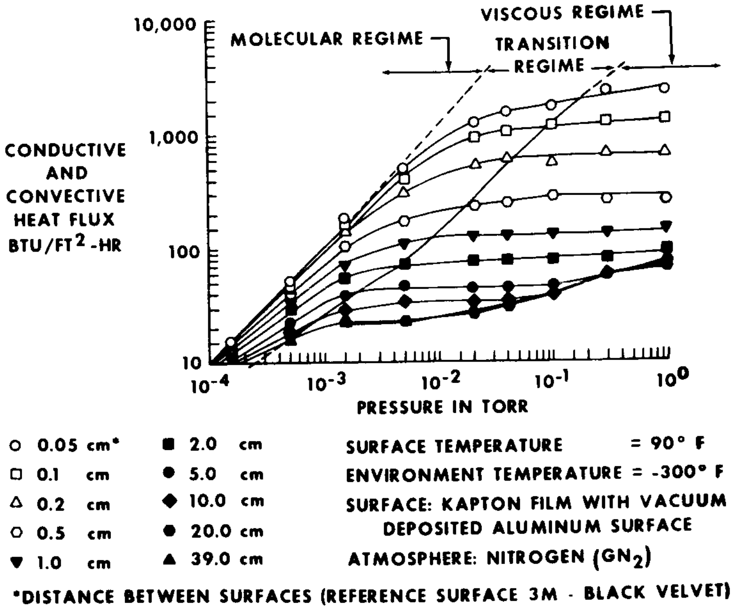

Figure 3

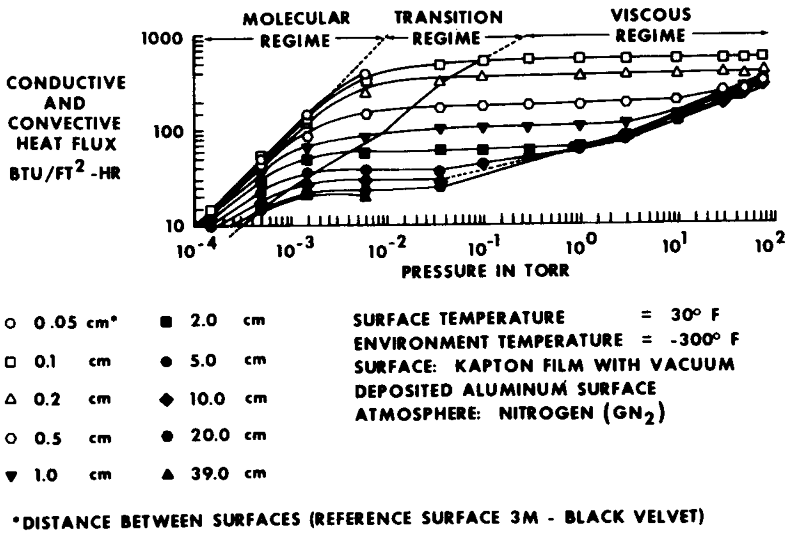

Figure 4

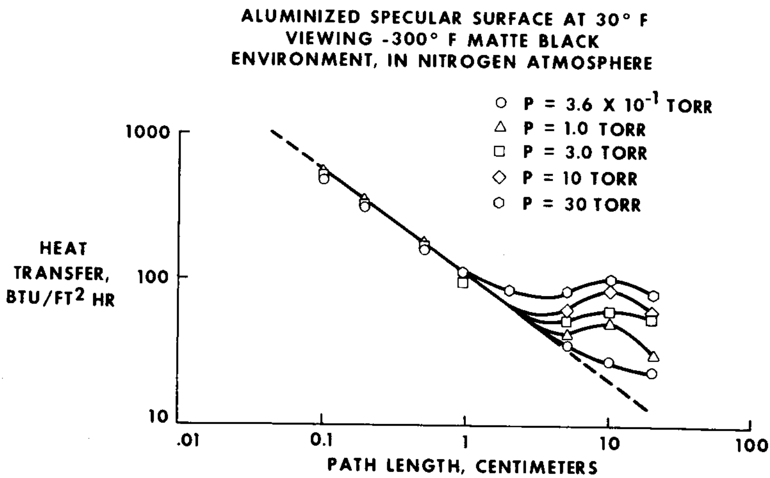

Figure 5.- Heat transfer as a function of distance between surfaces.

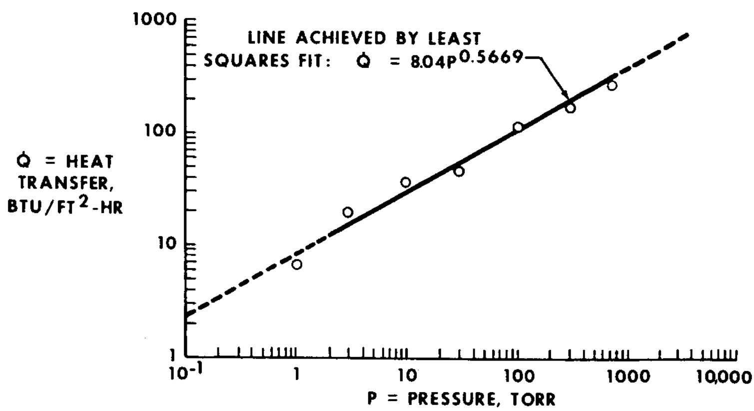

Figure 6.- Natural convective heat transfer as a function of a pressure vertical specular aluminized surface at 30 F in -300 F matte black environment, nitrogen gas.